

GAUGE AND HIGGS BOSONS

γ

$$I(J^P C) = 0,1(1^{--})$$

Mass $m < 1 \times 10^{-18}$ eVCharge $q < 1 \times 10^{-35}$ eMean life $\tau = \text{Stable}$ **g**

or gluon

$$I(J^P) = 0(1^-)$$

Mass $m = 0$ [a]

SU(3) color octet

graviton

$$J = 2$$

Mass $m < 7 \times 10^{-32}$ eV**W**

$$J = 1$$

Charge = ± 1 eMass $m = 80.385 \pm 0.015$ GeV $m_Z - m_W = 10.4 \pm 1.6$ GeV $m_{W^+} - m_{W^-} = -0.2 \pm 0.6$ GeVFull width $\Gamma = 2.085 \pm 0.042$ GeV $\langle N_{\pi^\pm} \rangle = 15.70 \pm 0.35$ $\langle N_{K^\pm} \rangle = 2.20 \pm 0.19$ $\langle N_p \rangle = 0.92 \pm 0.14$ $\langle N_{\text{charged}} \rangle = 19.39 \pm 0.08$ W^- modes are charge conjugates of the modes below.

| w+ DECAY MODES | | Fraction (Γ_i/Γ) | Confidence level | (MeV/c) ^p | |
|-----------------------|-----|--------------------------------|------------------|----------------------|----------|
| $\ell^+ \nu$ | [b] | $(10.80 \pm 0.09) \%$ | | — | DESIG=7 |
| $e^+ \nu$ | | $(10.75 \pm 0.13) \%$ | | 40192 | DESIG=1 |
| $\mu^+ \nu$ | | $(10.57 \pm 0.15) \%$ | | 40192 | DESIG=2 |
| $\tau^+ \nu$ | | $(11.25 \pm 0.20) \%$ | | 40173 | DESIG=5 |
| hadrons | | $(67.60 \pm 0.27) \%$ | | — | DESIG=8 |
| $\pi^+ \gamma$ | | $< 8 \times 10^{-5}$ | 95% | 40192 | DESIG=6 |
| $D_s^+ \gamma$ | | $< 1.3 \times 10^{-3}$ | 95% | 40168 | DESIG=9 |
| cX | | $(33.4 \pm 2.6) \%$ | | — | DESIG=12 |
| $c\bar{s}$ | | $(31 \pm 13) \%$ | | — | DESIG=10 |
| invisible | [c] | $(1.4 \pm 2.9) \%$ | | — | DESIG=11 |

Z

$$J = 1$$

Charge = 0

Mass $m = 91.1876 \pm 0.0021$ GeV [d]Full width $\Gamma = 2.4952 \pm 0.0023$ GeV $\Gamma(\ell^+ \ell^-) = 83.984 \pm 0.086$ MeV [b] $\Gamma(\text{invisible}) = 499.0 \pm 1.5$ MeV [e] $\Gamma(\text{hadrons}) = 1744.4 \pm 2.0$ MeV $\Gamma(\mu^+ \mu^-)/\Gamma(e^+ e^-) = 1.0009 \pm 0.0028$ $\Gamma(\tau^+ \tau^-)/\Gamma(e^+ e^-) = 1.0019 \pm 0.0032$ [f]

NODE=GXXX005

NODE=S000

NODE=S000M;DTYPE=M

NODE=S000Q;DTYPE=Q;CLUMP=Q

NODE=S000T;DTYPE=T;OUR EVAL;
→ UNCHECKED ←

NODE=G021

NODE=G021M;DTYPE=M;OUR EVAL;
→ UNCHECKED ←

NODE=G033

NODE=G033M;DTYPE=M

NODE=S043

NODE=S043Q;DTYPE=q;OUR EVAL;
→ UNCHECKED ←
NODE=S043M;DTYPE=M

NODE=S043MDZ;DTYPE=D

NODE=S043MD;DTYPE=D

NODE=S043W;DTYPE=G

NODE=S043PIC;DTYPE=K

NODE=S043KC;DTYPE=K

NODE=S043PRO;DTYPE=K

NODE=S043CHG;DTYPE=K

NODE=S043220;NODE=S043

DESIG=7

DESIG=1

DESIG=2

DESIG=5

DESIG=8

DESIG=6

DESIG=9

DESIG=12

DESIG=10

DESIG=11

NODE=S044

NODE=S044Q;DTYPE=q;OUR EVAL;
→ UNCHECKED ←
NODE=S044M;DTYPE=M

NODE=S044W;DTYPE=G

NODE=S044W4;DTYPE=w

NODE=S044W6;DTYPE=w

NODE=S044W5;DTYPE=w

NODE=S044R3;DTYPE=r

NODE=S044R19;DTYPE=r

Average charged multiplicity

$$\langle N_{\text{charged}} \rangle = 20.76 \pm 0.16 \quad (\text{S} = 2.1)$$

Couplings to leptons

$$\begin{aligned} g_V^\ell &= -0.03783 \pm 0.00041 \\ g_V^u &= 0.25^{+0.07}_{-0.06} \\ g_V^d &= -0.33^{+0.05}_{-0.06} \\ g_A^\ell &= -0.50123 \pm 0.00026 \\ g_A^u &= 0.50^{+0.04}_{-0.06} \\ g_A^d &= -0.523^{+0.050}_{-0.029} \\ g^{\nu\ell} &= 0.5008 \pm 0.0008 \\ g^{\nu e} &= 0.53 \pm 0.09 \\ g^{\nu\mu} &= 0.502 \pm 0.017 \end{aligned}$$

Asymmetry parameters [g]

$$\begin{aligned} A_e &= 0.1515 \pm 0.0019 \\ A_\mu &= 0.142 \pm 0.015 \\ A_\tau &= 0.143 \pm 0.004 \\ A_s &= 0.90 \pm 0.09 \\ A_c &= 0.670 \pm 0.027 \\ A_b &= 0.923 \pm 0.020 \end{aligned}$$

Charge asymmetry (%) at Z pole

$$\begin{aligned} A_{FB}^{(0\ell)} &= 1.71 \pm 0.10 \\ A_{FB}^{(0u)} &= 4 \pm 7 \\ A_{FB}^{(0s)} &= 9.8 \pm 1.1 \\ A_{FB}^{(0c)} &= 7.07 \pm 0.35 \\ A_{FB}^{(0b)} &= 9.92 \pm 0.16 \end{aligned}$$

| Z DECAY MODES | Fraction (Γ_i/Γ) | Scale factor/ Confidence level | p (MeV/c) | |
|--------------------------------------|--|-----------------------------------|--------------|----------------------|
| $e^+ e^-$ | (3.363 ± 0.004) % | | 45594 | NODE=S044215;DESIG=1 |
| $\mu^+ \mu^-$ | (3.366 ± 0.007) % | | 45594 | DESIG=2 |
| $\tau^+ \tau^-$ | (3.370 ± 0.008) % | | 45559 | DESIG=8 |
| $\ell^+ \ell^-$ | [b] (3.3658 ± 0.0023) % | | — | DESIG=16 |
| $\ell^+ \ell^- \ell^+ \ell^-$ | [h] (4.2 ± 0.9) $\times 10^{-6}$ | | 45594 | DESIG=82 |
| invisible | (20.00 ± 0.06) % | | — | DESIG=9 |
| hadrons | (69.91 ± 0.06) % | | — | DESIG=7 |
| $(u\bar{u} + c\bar{c})/2$ | (11.6 ± 0.6) % | | — | DESIG=21 |
| $(d\bar{d} + s\bar{s} + b\bar{b})/3$ | (15.6 ± 0.4) % | | — | DESIG=22 |
| $c\bar{c}$ | (12.03 ± 0.21) % | | — | DESIG=17 |
| $b\bar{b}$ | (15.12 ± 0.05) % | | — | DESIG=6 |
| $b\bar{b}b\bar{b}$ | (3.6 ± 1.3) $\times 10^{-4}$ | | — | DESIG=73 |
| ggg | < 1.1 % | CL=95% | — | DESIG=64 |
| $\pi^0 \gamma$ | < 5.2 | $\times 10^{-5}$ CL=95% | 45594 | DESIG=10 |
| $\eta \gamma$ | < 5.1 | $\times 10^{-5}$ CL=95% | 45592 | DESIG=11 |
| $\omega \gamma$ | < 6.5 | $\times 10^{-4}$ CL=95% | 45590 | DESIG=48 |
| $\eta'(958) \gamma$ | < 4.2 | $\times 10^{-5}$ CL=95% | 45589 | DESIG=12 |
| $\gamma \gamma$ | < 5.2 | $\times 10^{-5}$ CL=95% | 45594 | DESIG=13 |
| $\gamma \gamma \gamma$ | < 1.0 | $\times 10^{-5}$ CL=95% | 45594 | DESIG=14 |
| $\pi^\pm W^\mp$ | [i] < 7 | $\times 10^{-5}$ CL=95% | 10162 | DESIG=18 |
| $\rho^\pm W^\mp$ | [i] < 8.3 | $\times 10^{-5}$ CL=95% | 10136 | DESIG=19 |
| $J/\psi(1S) X$ | (3.51 ± 0.23) $\times 10^{-3}$ | S=1.1 | — | DESIG=23 |
| $\psi(2S) X$ | (1.60 ± 0.29) $\times 10^{-3}$ | | — | DESIG=60 |
| $\chi_{c1}(1P) X$ | (2.9 ± 0.7) $\times 10^{-3}$ | | — | DESIG=42 |
| $\chi_{c2}(1P) X$ | < 3.2 | $\times 10^{-3}$ CL=90% | — | DESIG=65 |

| | | | | |
|-------------------------------|------------------------------------|-------------------------|---|----------|
| $\gamma(1S) X + \gamma(2S) X$ | (1.0 ± 0.5) $\times 10^{-4}$ | - | DESIG=69 | |
| $\gamma(3S) X$ | seen | - | | |
| $\gamma(1S) X$ | < 4.4 | $\times 10^{-5}$ CL=95% | - | DESIG=66 |
| $\gamma(2S) X$ | < 1.39 | $\times 10^{-4}$ CL=95% | - | DESIG=67 |
| $\gamma(3S) X$ | < 9.4 | $\times 10^{-5}$ CL=95% | - | DESIG=68 |
| $(D^0/\bar{D}^0) X$ | (20.7 ± 2.0) % | - | DESIG=43 | |
| $D^\pm X$ | (12.2 ± 1.7) % | - | DESIG=44 | |
| $D^*(2010)^\pm X$ | [i] (11.4 ± 1.3) % | - | DESIG=24 | |
| $D_{s1}(2536)^\pm X$ | (3.6 ± 0.8) $\times 10^{-3}$ | - | DESIG=75 | |
| $D_{sJ}(2573)^\pm X$ | (5.8 ± 2.2) $\times 10^{-3}$ | - | DESIG=76 | |
| $D^{*/}(2629)^\pm X$ | searched for | - | DESIG=74;OUR EVAL; \rightarrow UNCHECKED \leftarrow | |
| $B^+ X$ | [j] (6.08 ± 0.13) % | - | DESIG=77 | |
| $B_s^0 X$ | [j] (1.59 ± 0.13) % | - | DESIG=49 | |
| $B_s^+ X$ | searched for | - | DESIG=70;OUR EVAL; \rightarrow UNCHECKED \leftarrow | |
| $\Lambda_c^+ X$ | (1.54 ± 0.33) % | - | DESIG=78 | |
| $\Xi_c^0 X$ | seen | - | DESIG=80;OUR EST; \rightarrow UNCHECKED \leftarrow | |
| $\Xi_b X$ | seen | - | DESIG=81;OUR EST; \rightarrow UNCHECKED \leftarrow | |
| b -baryon X | [j] (1.38 ± 0.22) % | - | DESIG=79 | |
| anomalous $\gamma +$ hadrons | [k] < 3.2 | $\times 10^{-3}$ CL=95% | - | DESIG=31 |
| $e^+ e^- \gamma$ | [k] < 5.2 | $\times 10^{-4}$ CL=95% | 45594 | DESIG=3 |
| $\mu^+ \mu^- \gamma$ | [k] < 5.6 | $\times 10^{-4}$ CL=95% | 45594 | DESIG=4 |
| $\tau^+ \tau^- \gamma$ | [k] < 7.3 | $\times 10^{-4}$ CL=95% | 45559 | DESIG=29 |
| $\ell^+ \ell^- \gamma\gamma$ | [l] < 6.8 | $\times 10^{-6}$ CL=95% | - | DESIG=45 |
| $q\bar{q}\gamma\gamma$ | [l] < 5.5 | $\times 10^{-6}$ CL=95% | - | DESIG=46 |
| $\nu\bar{\nu}\gamma\gamma$ | [l] < 3.1 | $\times 10^{-6}$ CL=95% | 45594 | DESIG=47 |
| $e^\pm \mu^\mp$ | LF [i] < 1.7 | $\times 10^{-6}$ CL=95% | 45594 | DESIG=5 |
| $e^\pm \tau^\mp$ | LF [i] < 9.8 | $\times 10^{-6}$ CL=95% | 45576 | DESIG=25 |
| $\mu^\pm \tau^\mp$ | LF [i] < 1.2 | $\times 10^{-5}$ CL=95% | 45576 | DESIG=26 |
| $p e$ | L,B < 1.8 | $\times 10^{-6}$ CL=95% | 45589 | DESIG=71 |
| $p \mu$ | L,B < 1.8 | $\times 10^{-6}$ CL=95% | 45589 | DESIG=72 |

Higgs Bosons — H^0 and H^\pm

H^0 Mass $m = 125.9 \pm 0.4$ GeV

Mass Limits for the Standard Model Higgs

Mass $m > 115.5$ and none 127–600 GeV, CL = 95%

The limits for H_1^0 and A^0 in supersymmetric models refer to the m_h^{\max} benchmark scenario for the supersymmetric parameters.

H_1^0 in Supersymmetric Models ($m_{H_1^0} < m_{H_2^0}$)

Mass $m > 92.8$ GeV, CL = 95%

A^0 Pseudoscalar Higgs Boson in Supersymmetric Models [n]

Mass $m > 93.4$ GeV, CL = 95% $\tan\beta > 0.4$

H^\pm Mass $m > 79.3$ GeV, CL = 95%

| H^0 DECAY MODES | Fraction (Γ_i/Γ) | p (MeV/c) | |
|-------------------|--------------------------------|-------------|--|
| WW^* | seen | - | |
| $Z Z^*$ | seen | - | |
| $\gamma\gamma$ | seen | - | |
| bb | possibly seen | - | |
| $\tau^+ \tau^-$ | possibly seen | - | |

Heavy Bosons Other Than Higgs Bosons, Searches for

Additional W Bosons

W' with standard couplings

Mass $m > 2.630 \times 10^3$ GeV, CL = 95%

NODE=S055

NODE=S055HBM;DTYPE=M

CLUMP=A

NODE=S055H;DTYPE=M;CLUMP=A;OUR EVAL

CLUMP=S

NODE=S055HSS;DTYPE=M;CLUMP=S

CLUMP=H

NODE=S055HSP;DTYPE=M;CLUMP=H

NODE=S055HGC;DTYPE=M;CLUMP=Z

NODE=S055220;DESIG=1;OUR EVAL

DESIG=2;OUR EVAL

DESIG=3;OUR EVAL

DESIG=4;OUR EVAL

DESIG=5;OUR EVAL

NODE=S056

CLUMP=A

NODE=S056W1C;DTYPE=M;CLUMP=A

Additional Z Bosons

Z'_{SM} with standard couplings

Mass $m > 2.330 \times 10^3$ GeV, CL = 95% ($p\bar{p}$ direct search)

Mass $m > 1.500 \times 10^3$ GeV, CL = 95% (electroweak fit)

Z_{LR} of $SU(2)_L \times SU(2)_R \times U(1)$ (with $g_L = g_R$)

Mass $m > 630$ GeV, CL = 95% ($p\bar{p}$ direct search)

Mass $m > 1162$ GeV, CL = 95% (electroweak fit)

Z_χ of $SO(10) \rightarrow SU(5) \times U(1)_\chi$ (with $g_\chi = e/\cos\theta_W$)

Mass $m > 1.970 \times 10^3$ GeV, CL = 95% ($p\bar{p}$ direct search)

Mass $m > 1.141 \times 10^3$ GeV, CL = 95% (electroweak fit)

Z_ψ of $E_6 \rightarrow SO(10) \times U(1)_\psi$ (with $g_\psi = e/\cos\theta_W$)

Mass $m > 2.000 \times 10^3$ GeV, CL = 95% ($p\bar{p}$ direct search)

Mass $m > 476$ GeV, CL = 95% (electroweak fit)

Z_η of $E_6 \rightarrow SU(3) \times SU(2) \times U(1) \times U(1)_\eta$ (with $g_\eta = e/\cos\theta_W$)

Mass $m > 1.870 \times 10^3$ GeV, CL = 95% ($p\bar{p}$ direct search)

Mass $m > 619$ GeV, CL = 95% (electroweak fit)

Scalar Leptoquarks

Mass $m > 830$ GeV, CL = 95% (1st generation, pair prod.)

Mass $m > 304$ GeV, CL = 95% (1st gener., single prod.)

Mass $m > 840$ GeV, CL = 95% (2nd gener., pair prod.)

Mass $m > 73$ GeV, CL = 95% (2nd gener., single prod.)

Mass $m > 525$ GeV, CL = 95% (3rd gener., pair prod.)

(See the Particle Listings for assumptions on leptoquark quantum numbers and branching fractions.)

Axions (A^0) and Other Very Light Bosons, Searches for

The standard Peccei-Quinn axion is ruled out. Variants with reduced couplings or much smaller masses are constrained by various data.

The Particle Listings in the full Review contain a Note discussing axion searches.

The best limit for the half-life of neutrinoless double beta decay with Majoron emission is $> 7.2 \times 10^{24}$ years (CL = 90%).

CLUMP=B

NODE=S056Z1C;DTYPE=M;CLUMP=B

NODE=S056Z12;DTYPE=M;CLUMP=B;
OUR EVAL;→UNCHECKED ←
NODE=S056ZLR;DTYPE=M;CLUMP=B

NODE=S056ZL2;DTYPE=M;CLUMP=B;
OUR EVAL;→UNCHECKED ←
NODE=S056ZCH;DTYPE=M;CLUMP=B

NODE=S056ZC2;DTYPE=M;CLUMP=B;
OUR EVAL;→UNCHECKED ←
NODE=S056ZPS;DTYPE=M;CLUMP=B

NODE=S056ZP2;DTYPE=M;CLUMP=B;
OUR EVAL;→UNCHECKED ←
NODE=S056ZET;DTYPE=M;CLUMP=B

NODE=S056ZE2;DTYPE=M;CLUMP=B;
OUR EVAL;→UNCHECKED ←
CLUMP=C

NODE=S056EG1;DTYPE=M;CLUMP=C;
OUR EVAL;→UNCHECKED ←
NODE=S056EG2;DTYPE=M;CLUMP=C;
OUR EVAL;→UNCHECKED ←
NODE=S056EG3;DTYPE=M;CLUMP=C;
OUR EVAL;→UNCHECKED ←
NODE=S056EG5;DTYPE=M;CLUMP=C;
OUR EVAL;→UNCHECKED ←
NODE=S056EG4;DTYPE=M;CLUMP=C;
OUR EVAL;→UNCHECKED ←

NODE=S029

NOTES

- [a] Theoretical value. A mass as large as a few MeV may not be precluded.
- [b] ℓ indicates each type of lepton (e , μ , and τ), not sum over them.
- [c] This represents the width for the decay of the W boson into a charged particle with momentum below detectability, $p < 200$ MeV.
- [d] The Z -boson mass listed here corresponds to a Breit-Wigner resonance parameter. It lies approximately 34 MeV above the real part of the position of the pole (in the energy-squared plane) in the Z -boson propagator.
- [e] This partial width takes into account Z decays into $\nu\bar{\nu}$ and any other possible undetected modes.
- [f] This ratio has not been corrected for the τ mass.
- [g] Here $A \equiv 2g_V g_A / (g_V^2 + g_A^2)$.
- [h] Here ℓ indicates e or μ .
- [i] The value is for the sum of the charge states or particle/antiparticle states indicated.
- [j] This value is updated using the product of (i) the $Z \rightarrow b\bar{b}$ fraction from this listing and (ii) the b -hadron fraction in an unbiased sample of weakly decaying b -hadrons produced in Z -decays provided by the Heavy Flavor Averaging Group (HFAG, http://www.slac.stanford.edu/xorg/hfag/osc/PDG_2009/#FRACZ).
- [k] See the Z Particle Listings for the γ energy range used in this measurement.
- [l] For $m_{\gamma\gamma} = (60 \pm 5)$ GeV.
- [n] The limits assume no invisible decays.

LINKAGE=GSS

LINKAGE=DXX

LINKAGE=WIN

LINKAGE=SZL

LINKAGE=ZZL

LINKAGE=TM

LINKAGE=ZA

LINKAGE=LEM

LINKAGE=SG

LINKAGE=HFF

LINKAGE=GDZ

LINKAGE=DYY

LINKAGE=HS